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Per Unit Cost Calculation of a Stand Alone PV System Considering the Equipment Cost

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Abstract

This paper contains the per unit cost Calculation of standalone Photovoltaic Systems (Home Solar Electricity) for residential use. In this paper on the photovoltaic system, the overall approach will be: First calculate the cost of each major component in terms of user specified variables. The user specified variables are taken at Peak power as what is required to power appliances and energy total consumed per day on average Hours of sunshine. After calculating the components costs, we add them up to create simple formulas with which to answer each of the questions above. The major components of a solar PV system are inverter, solar panels and Batteries. Inverter is a device that converts DC power into AC power at desire output voltage and frequency. This will help us to use home appliances and its major part of producing solar PV system.

Keywords: *Inverter, solar panel, battery.*

INTRODUCTION

The main sources of world's energy generation are the fossil fuels (gas, oil, coal) and nuclear power plants. Due to the usage of fossil fuels, greenhouse gases (CFC, CH_4, O_3, but mainly CO_2) emit into the atmosphere. From the nuclear power plant, carbon is released in a small amount (90 grams equivalent of carbon dioxide per kilowatt hour) [1]. For this the radioactive waste will cause harm to environment and remain active for thousand years which is a threat to human and living creatures and environments.

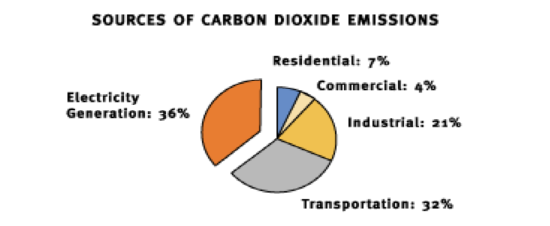

Fig 1: *Sources of carbon dioxide emissions.*

Figure 1 shows that the highest amount of carbon dioxide releases for electricity generation. Which leads to the global Warming issue and as also environmental pollution too.

From the Perspective of global warming and shortage of natural gas, scientists and engineers are looking for clean, renewable energies. Solar energy is the one of the best options. Because the earth receives 3.8 YJ [1YJ = 1024 J] of energy which is 6000 times greater than the worlds consumption. [2]

Bangladesh is facing shortage of energy. There are different sources like Coal, hydroelectric, natural gas. Among them Natural gas is the main source of electricity produce in Bangladesh. But for the limited gas supply might not fulfill the needs of commercial demands and industrial demands.

Due to upward demand on the energy sector for rapid population growth, food production, living standards needs and industrialization for economic growth etc. The Solar energy can be utilize for power generation in Bangladesh.

Considering above perspective, Solar Energy option for the Residential premises is being studied in this work.

INVERTERS

Inverter is device that converts DC power into AC power at desire output voltage and frequency is called an Inverter. Inverter have taken of modern role of modern technological world due to the use of using renewable energy. The main basic is that Inverters converts DC to AC Power. It also are used in uninterruptable power supply, control of electrical devices and active power filter.

Classification of Inverters

Based on their operation the inverters can be broadly classified into two types,

1. Current Source Inverter (CSI)
2. Voltage Source Inverter (VSI)

A Current Source Inverter which converts input direct current into an alternating current. Where the Input current remains same which is adjustable and output voltage of the inverter which is independent.

A voltage source inverter is one where the independently controlled AC output is a voltage waveform. This type of inverter is fed by a DC source of small internal impedance.

Circuit configuration of Inverter can be classified into two types,

1. Half Bridge Inverter.
2. Full Bridge Inverter

Half Bridge Inverter

In the half bridge inverter a two switching devices are used and two devices that replaced by capacitor. But for the Single-phase voltage source half-bridge inverters are meant for lower voltage applications and are commonly used in power supplied.

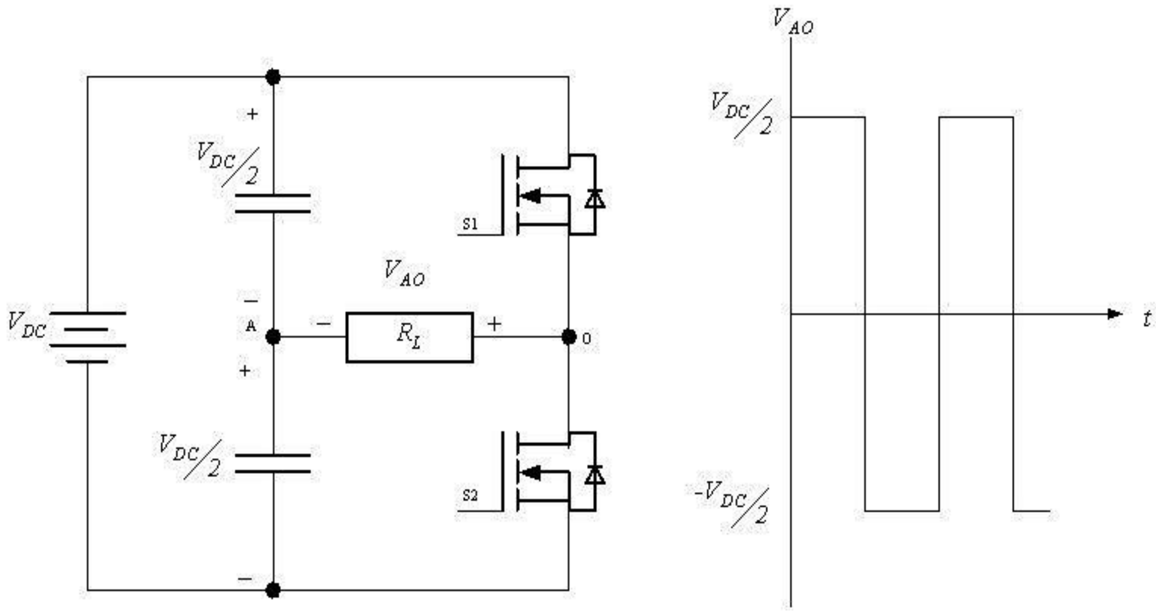

Fig 2: *Half Bridge inverter and its Output.*

Full Bridge Inverter

The full-bridge inverter is similar to the half bridge-inverter but it has an additional leg to connect the neutral point to the load. The main purpose to avoid shorting out the voltage source.

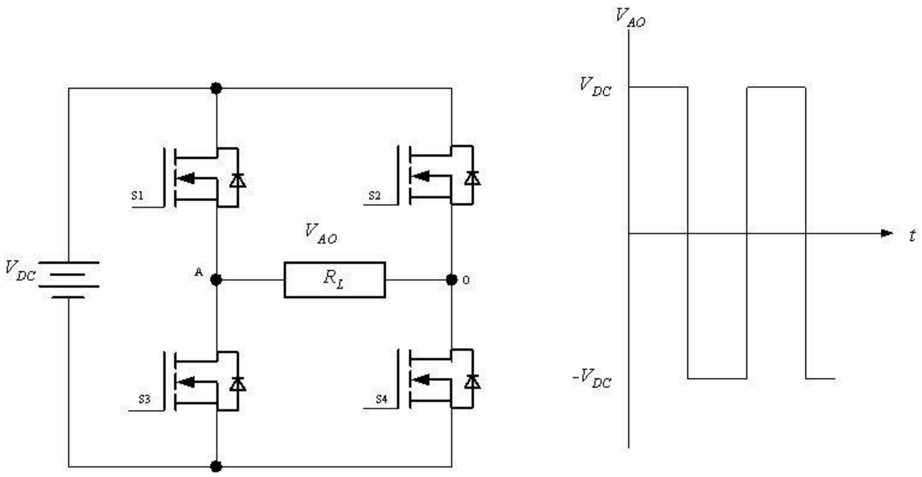

Fig 3: *Full Bridge Inverter and its output.*

Nature of Output Voltage of Inverter can be broadly three types,

1. Square Wave
2. Sine Wave
3. Modified Square Wave
4. Square Wave

A square wave is a periodic wave form at steady frequency between fixed minimum and maximum values where the square wave is non-sinusoidal.

Sine Wave

A curve representing a smooth sinusoidal wave where AC waveform is referred to as a Sine wave inverter.

Modified Square Wave

Modified square wave has a step space between the square waves which reduces the distortion that shows problem on electrical devices.

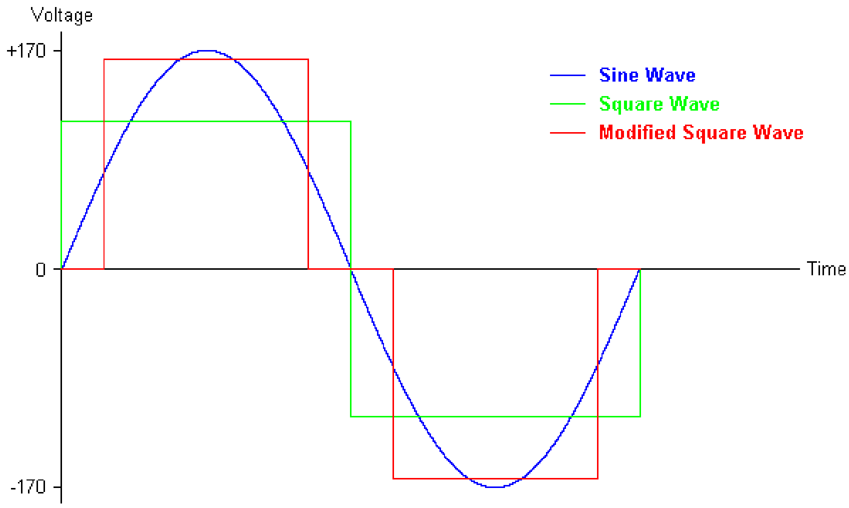

Fig 4: *Square wave, Sine wave and Modified Sine Square wave Inverter.*

SOLAR PANEL

PV Modules

This is the prime element of a PV system. This power which produces electricity from Sun light. The module where solar cells in it connected in series and parallel. The task of PV module is to convert the solar energy to electrical energy. When light shines on a PV cell the absorbed light generates electricity [3].

Solar Cells and how it works

Solar cells are mostly made of silicon where the silicon atom has four electrons in its outermost valence shell. To complete the shell and achieve the most stable configuration, the atom would like to have eight instead. To achieve this, each silicon atom shares each of its four electrons with four other silicon atoms. The sharing of atoms combine the atoms to each other, and these bonds are called "covalent" bonds. This bonds actually works out to the system.

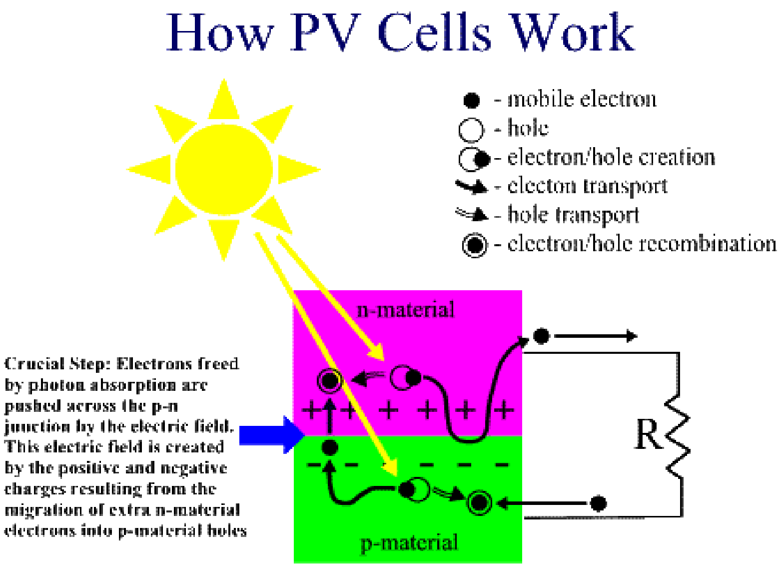

***Fig 5:** Diagram of how PV cells Works by showing the whole process.*

How PV cells are packaged

Each individual PV cell is about 1/2 inch to 4 inches in size which produce from 1 to 2 watts of power. Many cells are electricity wired together into a larger for to produce more power.

System Components

The basic components of a PV system are:

- PV panels
- Batteries
- Charge controller
- Inverter

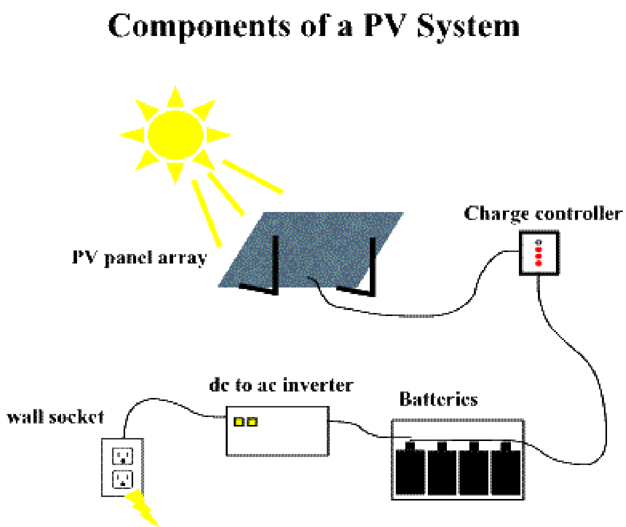

***Fig 6:** Components of a PV system.*

Types of PV Modules
There are currently four commercial production technologies for PV Modules [4]:
1. Single Crystalline
2. Polycrystalline or Multicrystalline
3. String Ribbon
4. Amorphous or Thin Film

Single Crystalline
Single crystalline solar cell is made up from silicon ingots and are in a shape cylindrical which have high efficiency. This Module efficiency averages about 10% to 12%.

Polycrystalline or Multi-crystalline
Polycrystalline is form of high purity silicon which is also called Polysilicon. The module efficiency is up to about 10% to 11%.

String Ribbon
This is a refinement of polycrystalline production; there is less work in production so costs are even lower. Module efficiency averages 7% to 8%.

Amorphous or Thin Film
Silicon material is vaporized and deposited on glass or stainless steel. The cost is lower than any other method. Module efficiency averages 5% to 7%.

Photovoltaic Array
A Photovoltaic Array consists of a number of individual PV modules or panels that have been wired together consisting of any number of modules. An array can be as small as a single pair of modules or large acres.

Type of PV system:
Types of solar system design: There can be various types of solar system design. But there are three basic design consideration, they are-

Grid Tie: A grid-tied electrical system that is also called tied to grid or grid tie system.

Off-Grid: Off-the-grid mainly generates solar electricity which designed for remote areas where the systems are designed to function without the support Utility grid. Off-Grid system can be operating anywhere and it is independent from the utility grid.

Stand alone: A stand-alone power system is known as remote area power supply of an off-the-rid electricity system.
Basically the area or the location that are not obtained with grid electricity distribution system.

BATTERY

Battery
Battery is a form of energy which can stored in a way is called battery. Battery is the heart of our system.

Basic of Battery in PV System
In Solar PV system batteries have to charge from solar panels and as the battery storage fill up with energy it disconnects which is a random in solar system. Basically the life time of a battery relays on charging and discharging. So the ratings of a battery depended according to cycle. Car battery is shallow cycled which types of battery have cycles between 10% - 15% of batteries total capacity. In other hand solar energy system has deep cycle batteries which have up to 50% - 80% of total battery's capacity. Deep cycle batteries are capable of many repeated deep cycles and best for solar power system [5].

Available Types of Batteries
There are many types of batteries found all around the world but only these four types of batteries are commonly used with the appliances we are using in our system.
1. RV or Marine type deep cycle Battery
2. Lead- acid Battery
3. AGM Battery
4. Gel Battery

RV or Marine type deep cycle Battery
These are basically used for boats and camps where small loads are needed to get powered. These types of batteries do not have capacity for continuous service with charger or discharger.

Lead- Acid Battery
Lead acid batteries can be used for solar energy storage. These types of batteries are deep cycled and have long life time for charging and discharging. Typical life time of lead- acid batteries is 3- 5 years.

AGM Battery
AGM stands for "Absorbent glass materials" where the battery is sealed with lead acid. The acid in the battery absorbed by glass materials. This type of battery is known as AGM Battery.

Gel Battery
The Gel Cell is similar to the AGM style because the electrolyte is suspended, but different because technically the AGM battery is still considered to be a wet cell.

Local Survey
Surveying some local companies, we found a list of batteries that are mostly available throughout our country. Most of these batteries are being imported from other countries table 1 shows the list of batteries available [6].

Table 1: *List and description of locally available batteries.*

Sl. No.	Battery Type	Volts	AH @20 Hr.	Length	Width	Height	Approximate Market Price (Tk)	Container Type
1	AP50	12	50	258	170	221	4,500.00	PP
2	AP70	12	70	302	170	227	6,100.00	PP
3	AP100	12	100	415	178	255	9,000.00	PP
4	AP120	12	120	500	182	255	10,070.00	PP
5	AP150	12	150	505	221	255	11,420.00	PP
6	AP200	12	200	514	275	255	12,980.00	PP

Battery Selection
For a PV system we have to select batteries which will relays on price, efficiency, longevity. So, taking into consideration of economic factor and availability in our country we have to Lead acid batteries. Which is used here widely for a solar PV system.

Here we will be using batteries of 200 Ah and 12 V, as our systems nominal voltage is 12V. Considering the prices of the locally available batteries we have decided to use batteries of 200 Ah, which will be the most economic battery for our system.

Charge Controller
Charge controller is and equipment which controls the charging system of the battery [7].

PER UNIT COST CALCULATION

Calculation of the cost of Photovoltaic Systems [8]

First we have to calculate the cost of each major component in terms of user specified variables. The major components are:

- Inverter : 320 watt – 14,000/- ~ 180$
- Solar Panels: 500 watt – 30,000/- ~ 390$
- Batteries : 200 Ah – 13,000/- ~ 170$

We will ignore adding in the cost of the charge controller, since this is only a few hundred dollars (whereas the whole system cost will be in the thousands of dollars).
The user specified variables will be [8]:

- Peak power required to power appliances
- Total energy produced/consumed per day
- Hours of sunshine (average)

After calculating the component costs, we add them up to create simple formulas with which to answer the per unit cost of the solar electricity.

AC load Load Calculations

While designing a PV system we have to calculate the load that will be connected to the system. According to that load requirement we have to design the PV system. In the PV system we will be using the Units ampere hour (AH) and watt hour (WH). For further calculation we will Measure the total wattage and peak current also. In this PV system we are developing a design that provide backup power for a families, the family having Two 75W fans, four 23 W CFL bulb connected to the system.

Load Calculations

Summer and winter load calculation processes are same. Only difference is in dally load usages. As in summer there are more load shedding the load shedding time usages will be larger than winter.

Table 2: *Description of the loads connected to the System.*

Load Description	**LOAD Power (Watt)**	**QTY**	**Watt**
Drawing/Dining room light	23	1	23
Dining room fan	75	1	75
bedroom light	23	1	23
bedroom fan	75	1	75
Kitchen light	23	1	23
Toilet light	23	1	23
Total			**242**

A certain amount of load is allocated for each family in this system. An example of the total load is shown in table with various household appliances. Here the total load will be around 1694 Watt.

Cost of inverter as function of peak power required [8]

An Inverter is one of the main elements of PV system. As we know the inverter is an electrical device which converters direct current (DC) to alternating current (AC) for the voltage required in the system. So, in a PV system the Batteries produce power in direct current (DC) which can run at low voltages but not for the commonly used home appliances which eliminates more power. For this we need alternating current (AC) power by using Sine wave inverter. So, Inverters take the DC power from the battery and converts into AC power.

Recall that power is defined to be the rate at which energy is delivered (or captured), that is, energy per unit time [8]:

Power = Energy / Time

If we expect to run, four 23watt CLF bulbs and two 75watt fan, then the peak power would be:

$$P_{peak,\ usage} = 4 \times 23 \text{ watt} + 2 \times 75 \text{ watt} = 242 \text{ watts} = 0.242 \text{ kilowatts}$$

The amount of peak power the system can deliver will be determined by the size of the system's inverter, the inverter being the device which converts the dc battery power to ac:

$$P_{peak,\ usage} = P_{peak,\ inverter}$$

320 watt inverter cost $180

So, $180/320watt = $0.5625

As determined by surveying current market prices for inverters, the costs of an inverter are about $ 0.5625 per watt, or (multiplying by 1000):

$$Cost_{inverter} = \$562.5/\text{kilowatt}$$

Thus, the cost of the inverter, as a function of the peak power used, is therefore:

$$Cost_{inverter}(P_{peak,\ usage}) = P_{peak,\ usage} \times Cost_{inverter}$$

or

$$Cost_{inverter} = P_{peak,\ usage} \times \$562.5/\text{kilowatt}$$

For example, if we need 2 kilowatts of peak power used, the cost of the inverter will be about $2000 dollars.

Cost of solar panels as a function of energy usage

Solar Panel is the principal element of a PV system which produces electricity from Sun light. In a PV module there are many solar cells in it connected in series. The main task of PV module is to convert the solar energy to electrical energy. When light shines on a PV cell, the absorbed light generates electricity.

The peak power produced by the solar panels is determined by the type and number of solar panels one uses:

$P_{peak\ panels}$ = # of panels x power per panel
= 5 x 100 watt
= 500 watt

Although the energy used by the appliances will of course be produced by the solar panels, it is not necessary that the peak output of the solar panels be equal the peak power used:

$P_{peak,\ usage}$: NOT NECESSARILY EQUAL TO: $P_{peak\ panels}$

Instead, we should calculate the peak power of the solar panels, and hence the number of solar panels, from the total amount of energy we want them to produce each day.

Calling the energy produced $E_{produced}$, we want this to equal the amount of energy used each day,

Important connection: $E_{produced} = E_{used}$

We will specify energy in units of kilowatt-hours:

Energy = Power (in kilowatts) x Time (in hours) = # of kilowatt-hours
= 0.242 kilowatt x 7 hours
= 1.694 KiloWatt-Hour

A good target for E_{used} for an energy efficient home is 1-2 kilowatt-hours. Electrical energy from the grid in the Bangladesh typically costs between 5 to 10 cents per kilowatt-hour. So, for example, if you use 10 kilowatt-hours a day, and the cost of power is about 5 cents per kilowatt-hour, then you electrical costs would be about 50 cents (38.64/-) per day or $15 (1159.21/-) per month.

Also, we need to know how long the sun shines each day on average. Let this be denoted by T_{sun},

***Table 3:** This is the table of Estimated Sunshine GHI values from NASA [9]*

Table 1. GHI values for Month	NASA	Estimated (from unshine)	DLR [16] German Aerospace Center
Jan	4.84	4.00	4.63
Feb	5.46	4.44	5.04
Mar	6.41	5.37	5.62
Apr	6.48	5.87	6.47
May	5.96	5.43	4.94
June	3.60	4.10	3.39
Jul	3.62	3.87	3.31
Aug	3.69	3.95	3.78
Sept	4.34	4.09	3.96
Oct	4.72	4.21	4.28
Nov	4.42	3.72	4.54
Dec	4.54	3.75	4.16
Annual	4.84	4.40	4.50

By using the above table we got the estimated sunshine GHI values where

T_{sun} = 4.40 Hours of Sunshine on average [9].

Using the formula for power and energy (Power = Energy / Time), we have

$P_{peak\ panels} = E_{used} / T_{sun}$ = 1.694 KwH / 4.40 hours

As determined from a survey of current market prices, it costs about $390 to purchase and install a 500 watt panel. Therefore, the upfront cost of the solar panels *per watt* are
$Cost_{panels}$ = $390/500 watts = $.78/watt
Or, by multiplying numerator and denominator by 1000,
$Cost_{panels}$ = $390/500 watts = $780/kilo-watt

Thus, as a function of Energy use, the cost of the solar panels will be
$Cost_{panels} = P_{peak\ panels} \times Cost_{s.p.} = (E_{used} / T_{sun}) \times Cost_{s.p.}$
= (1.694 KWH/4.40 hour) x $780/kilo-watts
= $278.67
or

$Cost_{panels} = (E_{used} / T_{sun}) \times \$780$/kilo-watt

Number of Battery Required
To calculate the battery backup time load, we have to consider the usage of loads from afternoon to next morning when the bright sun shine will not be there. Considering that we will have the battery backup load calculations shown in table 4.

Table 4: *Battery backup load Calculations.*

Load Description	Ac Load Power(Watt)		Continious Duty Cycle (Aprox) (Hrs)	Watt Hour
Drawing/Dining room light	23	**x**	7	161
Dining room fan	75	**x**	7	525
bedroom light	23	**x**	7	161
bedroom fan	75	**x**	7	525
Kitchen light	23	**x**	7	161
Toilet light	23	**x**	7	161
Total				**1694**

Total Energy need for a home = 1694 Wh. It isn't good to run a battery all the way down to zero during each charge cycle. It is recommended to leave the battery 20% charged. So we are considering that 85% of the battery charge is usable.

So usable amount of charge = 1694 WH/ 0.85 = 1992.94 Ah
For lead acid batteries the rated capacity (i.e. the number of AH stamped on the side of the battery) is typically given for a 20 hour discharge rate. If you are discharging at a slow rate you will get the rated number of amp-hours out of them. However, at high discharge rates the capacity falls steeply. Drawing current at a rate of 60% of the rated number of amp-hours will give the best performance.

If the nominal battery voltage is 12 V
Then the battery should be rated = 1992.94 AH/ (0.6 x 12 v) = 276.79 Ah

By using 200 AH 12 Volt DC Battery we will need 2 batteries or more.

Cost of batteries as a function of energy usage
The amount of energy stored (by batteries) determines how much energy can be used after dark, or on a rainy day.
The number of kilowatt-hours we can store will be determined by the number and type of batteries we have:
E_{stored} = Energy per battery x number of batteries
The lifetimes of deep cycle batteries are fairly short (3 - 10 years), and depend on how well they are maintained (for example, one needs to avoid overcharging, and overdrawing, and in many cases to keep the water levels up). Typically, if a battery is discharged to 50% every day, it will last about twice as long as if it is cycled to 80%. If cycled only 10%, it will

last about 5 times as long as one cycled to 50%.

We will assume, in order not to discharge the battery more than 50%, that the batteries will be able to store twice the amount of energy we use:

E_{stored} = 2 x E_{used}
= 2 x 1.694 KWH
= 3.388 KWH ($170/1.694 KWH = $100.354)

Presently, the cost of batteries is about $100 per kilowatt-hour of storage:

$Cost_{batteries}$ = $100/kilowatt-hour

The cost of batteries, therefore, *as a function of energy used*, is

$Cost_{batteries}$ = 2 x E_{used} x $100/kilowatt-hour

Because we have included the factor of two, then we are probably safe to assume at least a six year lifetime on the batteries:

$Lifetime_{batteries}$ = 6 years

Calculation of upfront cost [8]

Adding up the costs of the inverter, panels and batteries, we find:

$Cost_{upfront}$ = $Cost_{inverter}$ + $Cost_{panels}$ + $Cost_{batteries}$
= $P_{peak,\ usage}$ x $1000/kw + ($E_{used}$ / T_{sun}) x $8000/kw + 2 x E_{used} x $100/kwh
= 0.242KW x $ 562.5/KW
+ (1.694kw/4.40hours)
x $780/KW + 2 x 1.694 x 100/KWH
= $775.225

Calculation of life-cycle cost per kilowatt-hour

As mentioned above, today's solar panels are estimated to last ***at least*** 25 years. We will therefore use 25 years as our lifetime with which to calculate the life-cycle cost [8]:

T_{system} = 25 years

Note that this figure is somewhat arbitrary: using a longer lifetime will tend to decrease the life-cycle cost calculated, and vice versa.

The total life-cycle cost per kilowatt hour is given by

$Cost_{kwh}$ = (Total life-cycle cost)/(Total kilowatt-hours used) [8].

To calculate the total life-cycle cost, we need to account for periodic replacement of the batteries. Assuming a lifetime of six years for the batteries (which we helped insure by sizing the battery to twice the daily energy usage), the number of times we have to replace the batteries is

$N_{batteries}$ = T_{system} / $Lifetime_{batteries}$ = 25 years/6 years = (approximately) 4 years

Then the total life-cycle cost of the batteries will therefore be

$Cost_{batteries,\ life-cycle}$ = 4 x $Cost_{batteries}$ = 8 x E_{used} x $100/kwh
= 8 x 1.694 x $100KWH
= $1355.2

The total life-cycle cost of the system will therefore be

$Cost_{life-cycle}$ = $Cost_{inverter}$ + $Cost_{panels}$ + $Cost_{batteries,\ life-cycle}$
= $P_{peak,\ usage}$ x $1000/kw + ($E_{used}$ / T_{sun}) x $8000/kw + 8 x E_{used} x $100/kwh
= 0.242KW x $562.5/KW + (1.694kw/4.40 hours) x $780/KW + 8 x 1.694 KWH
x 100/KWH
= $1791.625

Note that this is similar to the upfront cost formula, except for the extra factor of four in the last term.

Because we defined the quantity **E_{used}** to be the number of kilo-watt hours used per day, the number of kilowatt-hours used over the lifetime of the system will be [8]:

Total kilowatt-hours used = 25 years x 365 days x E_{used} = 9125 days x E_{used}.

We therefore have

$Cost_{kwh}$ = $Cost_{life-cycle}$ / (9125 x E_{used})
= $1791.625/(9125 days x 1.694 kwh)
= 0.1159 cents (8.64 taka)

After calculating the components we have found the per unit cost calculation of a standalone PV system where per unit cost around 9 taka. We can try to make the price a little low. If we get to work with the sections of the batteries and inverters maybe we can find a way where the price of per unit cost will decrease. If we use a new technology on this we can make a Standalone PV system more reliable to home users.

CONCLUSION

We are facing fuel shortage for electricity generation and in the near future the whole world going to face the same need because of limited fuel. So around the world renewable energy demand and research are sloping upwards. So, we choose solar energy for Residential areas as Subordinate energy source but here we have known about solar panel is a kind of Renewable Energy which means the energy that comes from natural resources and by natural resources we know as wind, tides, rain, sunlight and geothermal heat. These energies are acquired from natural processes that are restored. Electrical energy can be attained from solar, wind, ocean, hydropower, biomass, geothermal resources, befouls and hydrogen. If we can use renewable energy to produce power, we can certainly reduce the power shortage to some extends. Bangladesh has produced 5% of total power generation by 2015 and 10% by 2020 from renewable energy sources like air, waste and solar energy.

As we can say after we calculated the per unit cost calculation of a solar PV system, we can say Solar as the best form of renewable energy.

Bangladesh is situated between 20.30 - 26.38 degrees north and 88.04 - 92.44 degrees east which is an ideal location for solar energy utilization. Here daily average solar radiation varies between 4 to 6.5 kWh per square meter. Maximum amount of radiation is available on the month of March-April and minimum on December-January [10]. There is a good visibility of uses of solar power in Bangladesh. Solar energy is obtained from the sun through the solar radiation. In our case as we are finding a solution that what will be the Per unit cost of solar PV system for resident homes.

There are various renewable energy sources and among the rest we are going to work with Solar, as it is already being popular in our country but in a very narrow span.

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